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Sediment Toxicity, Contamination, and Macrobenthic Communities Near a Large Sewage Outfall

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Sediment Toxicity, Contamination, and Macrobenthic Communities Near a Large Sewage Outfall

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ABSTRACT: Sediment toxicity, contamination, and macrobenthic community structure were examined in 1980 at seven stations along a pollution gradient from the Los Angeles County Sanitation Districts' sewage outfalls on the Palos Verdes Shelf, CA, to control conditions in Santa Monica Bay. Sediment toxicity was determined by laboratory bioassays with the phoxocephalid amphipod, *Rhepoxynius abronius*. Distribution and abundance of the macrobenthos were generally consistent with the Pearson-Rosenberg model and the Bascom-Mearns-Word quantitative classification of macrobenthic assemblages. Species richness, density, and biomass increased greatly in areas of moderate sediment organic enrichment, but decreased to or below control conditions near the outfalls. The Infaunal Index of changes in benthic community structure in response to organic enrichment increased with distance from the outfalls. Dominant species changed from the opportunistic polychaete, *Capitella capitata*, near the outfalls; to the clam, *Parvilucina tenuisculpta*, and the polychaetes, *Mediomastus californiensis* and *Tharyx* sp. A in areas of moderate organic enrichment; to the brittlestar, *Amphiodia urtica*, at the control station. Sediment toxicity was significantly greater than control levels at the three stations closest (≤3 km) to the outfalls. There were significant increases in the concentration of most sediment contaminants and significant decreases in the richness and abundance of the benthos at stations where sediment was acutely toxic to *Rhepoxynius abronius*. Organic enrichment and anaerobic sediment conditions appear to be the dominant anthropogenic influences on the macrobenthos of the Palos Verdes Shelf. Toxicity caused by chemical contamination may contribute to the absence of amphipods near the sewage outfalls.

KEY WORDS: sediment toxicity, bioassay, sewage outfalls, benthos, amphipods, Southern California Bight, aquatic ecosystems

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Laboratory bioassays are often criticized for failing to accurately simulate the real world [*1–3*]. This criticism has prompted "field validation" research to test the ecological relevance of bioassays. Recent advances in bioassay methods have emphasized the advantages of toxicity tests applied to environmental samples rather than single contaminants [*4*]. A bioassay developed in our laboratory concerns the toxicity of field-collected sediment samples to the infaunal phoxocephalid amphipod, *Rhepoxynius abronius* [*5*]. This bioassay measures the gross toxicity of the complex mixture of contaminants that characterizes benthic pollution. Faunal surveys and bioassays of waste materials have shown that this species and many other amphipods have a low tolerance to sediment contamination [*6–11*]. The research reported here examines the relevance of this sediment bioassay to the effects of stress on a real benthic ecosystem.

Our research compares the toxicity of sediment collected along a benthic pollution gradient with macrobenthic community structure and chemical contamination along the same gradient. The pollution gradient lies on the Palos Verdes Shelf, CA, near the Los Angeles County Sanitation Districts' sewage outfalls. Approximately 1.4×10^9 L/day of effluents receiving primary treatment are discharged from these outfalls [*12*]. The discharge has contaminated the sediment with many inorganic and organic pollutants, and has greatly altered the composition and abundance of macrobenthic species [*2,12–14*].

Several *a priori* hypotheses were tested to determine relationships between the survival of *Rhepoxynius abronius* and ecological conditions on the Palos Verdes Shelf. The null hypotheses were the absence of significant correlation between survival and: (1) density of phoxocephalid amphipods; (2) density of amphipods of all species; (3) density, biomass, species richness, and other structural characteristics of the entire macrobenthic assemblage; (4) parameters of organic enrichment of sediment, for example, total volatile solids; and (5) parameters of chemical contamination of sediment, for example, metals. Clearly, the bioassay data would have no ecological relevance if they were not correlated with any of these parameters.

A second objective of our research was to test predictions of the Pearson and Rosenberg [*15*] model of macrobenthic succession in relation to organic enrichment. According to this model, the benthic assemblage near major sources of organic material contains only a few pollution-tolerant opportunistic species that may be represented by a high density of individuals, that is, the "peak of opportunists." The assemblage of opportunists is separated by an "ecotone point" from an assemblage of greater species richness and biomass that gradually changes through a "transition zone" into the assemblage characteristic of the unpolluted environment. Earlier investigations on the Palos Verdes Shelf identified large areas of increased biomass and density of the macrobenthos [*2,12–14*]. The present study used the Pearson-Rosenberg model in conjunction with the sediment bioassay to discriminate the effects of organic enrichment and sediment toxicity on the macrobenthos.

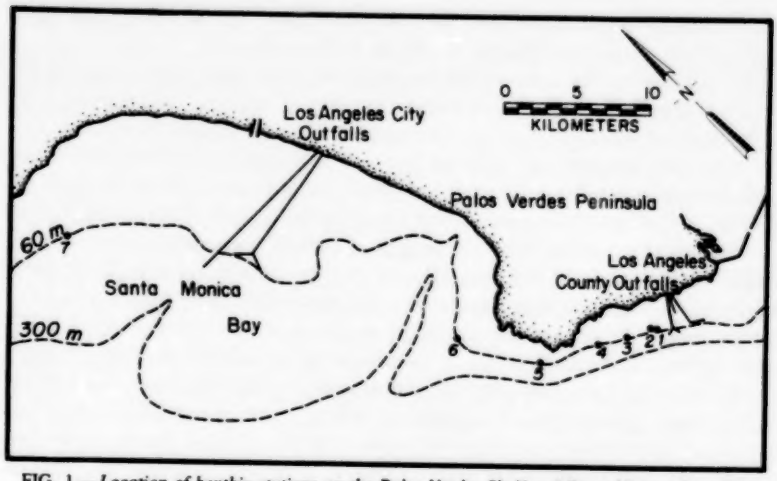

FIG. 1—*Location of benthic stations on the Palos Verdes Shelf and Santa Monica Bay, CA.*

Materials and Methods

Sediment and macrobenthos samples were collected at seven stations on the Palos Verdes Shelf and Santa Monica Bay, CA, on 13–15 May, 1980 (Fig. 1). The Los Angeles County Sanitation Districts' outfalls discharge at a water depth of approximately 60 m. All stations were located on the 60-m depth contour to the northwest of the outfalls in the direction of predominant benthic deposition of sewage particulates [*12*,*16*,*17*]. The first six stations were located at increasing distances of 1 to 15 km from the outfalls. The seventh station was 47 km from the outfalls in northwest Santa Monica Bay. This reference station is the closest site northwest of the study area that is representative of biological control conditions in the Southern California Bight [*18*,*19*]. Although the Los Angeles City sewage outfalls lie between the Palos Verdes Shelf and the control station, they have little or no influence on our pollution gradient or control stations (see Fig. 3 of Bascom et al [*13*]).

Ten 0.1-m^2 van Veen grab samples were collected at each station. The contents of five grabs were sieved separately through a 1.0-mm mesh screen to collect macrofauna. Material retained on the screen was preserved in buffered 10% formalin, later transferred to 70% ethanol, sorted to major phylogenetic group (Foraminifera, Mollusca, Polychaeta, Crustacea, Ophiuroidea, other Echinodermata, other taxa), and weighed (±0.1 g) after blotting on absorbent paper. After weighing, specimens were identified to the species level, where possible, and counted. Less than half of the invertebrate species in the Southern California Bight have been adequately described in the taxonomic literature [*2*]. Alphabetic codes were assigned to distinct species when complete taxonomic names were not available (for example, *Tharyx* sp. A). These codes sometimes reflect assign-

ments made by taxonomists (for example, *Myriochele* sp. M by the Southern California Association of Marine Invertebrate Taxonomists).

The structure of the macrobenthic community was analyzed in relation to species composition, species richness (number of species, S, collected per 0.1-m^2 grab), biomass (g/0.1 m^2, wet weight), density (number of individuals, N/0.1 m^2), dominance, and Infaunal Index. The dominance index was defined as the minimum number (or fraction) of species whose combined abundance was equal to 75% of the total number of individuals in the sample. The Infaunal Index is an empirically derived index of changes in benthic communities near sewage outfalls in the Southern California Bight [*6,20*]. Its value is based on the relative abundance of four groups of species representative of different stages of macrobenthic succession in response to organic enrichment (see Word [*6,20*] for the index formula and complete list of taxa included in each of the four groups). Species in Group I are representative of relatively unpolluted control areas. Word [*6,20*] placed phoxocephalid amphipods including the genus *Rhepoxynius* in Group I. Group IV includes many pollution indicator species (for example, the opportunistic polychaete, *Capitella capitata*) that are very abundant in areas of major organic enrichment. Groups II and III species are representative of intermediate phases of succession along organic pollution gradients. The value of the Infaunal Index varies from 0 when all individuals belong to Group IV to 100 when all individuals belong to Group I.

The remaining five grabs were used to obtain sediment samples for a variety of physical, chemical, and toxicological analyses. The van Veen grab was equipped with hinged top plates that permitted sampling of the sediment surface. Seawater overlying the sediment was drained from the grab. Redox potential (Eh) and pH were measured by inserting electrodes 1 cm beneath the sediment surface. Interstitial water was collected by suction into a syringe through a cellulose filter inserted into the sediment. This water was then passed through a 0.45 μm membrane filter and preserved with $HgCl_2$ (for ammonia-N analysis) and antioxidant buffer (for free sulfide analysis). Ammonia-N was analyzed by the automated indophenol blue system [*21*]. Free sulfide was measured within one week of collection by cadmium nitrate titration using a sulfide electrode. Separate, 2-cm-deep cores were taken to provide sediment from the upper 2-cm surficial layer for (1) amphipod bioassays, (2) particle size distribution and total volatile solids, (3) organic chemical analyses, and (4) inorganic chemical analyses. Sample preservation and analyses are shown in Table 1. All bulk sediment concentrations are expressed on a dry weight basis. Sediment samples for priority organic pollutants were collected from only two grabs at each station because of the high cost of these analyses. Samples from five grabs were taken for all other geochemical parameters.

Sediment bioassays were conducted with the phoxocephalid amphipod, *Rhepoxynius abronius* as described by Swartz et al [*5*]. The *R. abronius* and clean test sediment (control) were collected with a small dredge from lower Yaquina Bay, OR (44° 37′ 33″ N, 124° 02′ 58″ W). Adult amphipods (~4 mm total

TABLE 1 —*Analyses of geochemical samples.*

Parameter	Preservation/Storage	Method of Analysis
Total solids	Capped glass jar, 4°C	Determined from weight loss at 100°C for 15 h
Total volatile solids	Capped glass jar, 4°C	Determined from weight loss of dried sample heated to 550°C for 1 h
Total organic carbon	Freeze-dried in glass vial	Removal of carbonates with HCl; wet oxidation and measurement of CO_2 using an OIC carbon analyzer
5-day BOD	Capped glass jar, 4°C, analyzed within 3 days after collection	5-day dissolved O_2 utilized by wet sediment in BOD bottle filled with seawater at 20°C; a seeding solution of microorganisms was not added
Total oil/grease	Freeze-dried in glass vial	Soxhlet extraction with Freon and infrared spectrophotometry [*22*]
Hydrocarbon oil/grease	Freeze-dried in glass vial	Polar material removed from Freon extract above using silica gel and reanalyzed by infrared spectrophotometry [*22*]
Total sulfide	Frozen in sealed, open barrel 10 cm^3 syringe	Trapping of acid-liberated sulfides in antioxidant buffer; potentiometric titration of sulfide with cadmium
Metals (Cd, Pb, Zn, Cr, Cu, Ni)	Capped plastic jar, 4°C	Digested in concentrated HNO_3 several times to small volume; finally heated with 2 *M* HCl and filtered through Whatman 40 filter paper; atomic absorption analyses
Sand Silt/clay	Plastic bag, 4°C	Sieve method [*23*] Pipette method [*23*]
Priority pollutant organic compounds	Frozen in glass jars with Teflon-lined lids	Soxhlet extraction with 1:1 acetone/hexane, concentrate and extract into 2% NaOH for base-neutral fraction; extract acidified concentrate with methylene chloride for acid fraction; gas chromatography/mass spectrometry analyses of fractions

length) were removed by gently sieving sediment through a 1.0-mm screen. Amphipods were picked from material retained on the screen and maintained in sieved sediment until the bioassay was initiated three days later. A portion of the sediment that passed through the 1.0-mm screen was resieved through a 0.5-mm screen to remove juvenile amphipods and then stored at 4°C for use as the control sediment in the bioassay. The sediment was a well-sorted, fine-grained sand with an equivalent spherical diameter of 0.162 mm.

Bioassay chambers (1-L glass beakers) were filled to a depth of 2 cm with test sediment. A plastic disk was placed on the sediment surface as 600 ml of seawater (5 μm filtered, 25‰ salinity) were added to the chamber. Each beaker was covered with Parafilm and gently aerated through a 1-mL pipette that extended no closer than 2 cm from the sediment surface. Dissolved oxygen in the overlying water was not less than 7.0 mg/L for any treatment during the bioassay. At least a thin aerobic layer existed on the surface of all test sediments. The chambers were placed in a 15°C water bath and allowed to equilibrate overnight.

Five replicate bioassay chambers were prepared for the Yaquina Bay control sediment. A chamber was prepared for each of the bioassay samples from five grabs taken at each station. The bioassay was initiated by randomly distributing 20 *R. abronius* to each bioassay chamber along with 200 ml of seawater (final volume, 800 ml of seawater overlying sediment). Typically, the amphipods quickly swam to the bottom and burrowed into the sediment. After ten days, the contents of the beakers were sieved through a 0.5-mm screen and survivors counted.

Statistical comparisons of differences in mean values between stations for biological and geochemical parameters were made by *t*-tests, analysis of variance and Student-Newman-Keuls multiple range test, or, when variances were heterogeneous, the Games and Howell method [*24*,*25*]. Dunnett's procedure was used to compare mean survival in sediment from the Palos Verdes Shelf and Santa Monica Bay stations with mean survival in the Yaquina Bay control sediment [*25*]. Kendall's Coefficient was used for rank correlation of biological, geochemical, and toxicological parameters [*24*]. Unless otherwise noted, all statements about statistical comparisons are based on the $p < 0.05$ significance level.

Numerical classification analyses were applied to the biological and geochemical data sets to elucidate the relative similarity of samples collected on the 60-m transect. This procedure clusters samples on the basis of similarity in the composition and relative abundances of macrobenthic species or the presence and relative magnitude of geochemical parameters. The classification analyses were conducted using the Canberra metric dissimilarity coefficient and the flexible sorting strategy of Lance and Williams with $B = -0.25$ [*26*,*27*]. To reduce the biological data set to a manageable size, rare species represented by less than 20 individuals in the total survey were excluded, leaving 86 macrobenthic species for the classification. Geochemical parameters included in this analysis were Eh, pH, total solids, total volatile solids, total organic carbon, ammonia-nitrogen, free sulfide, total sulfide, five-day sediment biochemical oxygen de-

mand (BOD), total oil and grease, hydrocarbon oil and grease, cadmium, lead, zinc, chromium, copper, nickel, percent sand, percent silt, and percent clay. Data on organic priority pollutants were excluded from the classification, because they were available for only two samples from each station.

Results

Macrobenthos

A total of 319 species and 39 232 individuals were collected in the macrobenthic survey. Within-station faunal homogeneity was high relative to between-station homogeneity. The numerical classification of the biological data always placed individual replicates from the same station within the same cluster (Fig. 2). Replicates from Stations 1 and 2 clustered together. These stations were close together and almost equally distant from the outfalls. All other clusters represented replicates from a single station. The hierarchial arrangement of the macrobenthic sample clusters is consistent with a hypothesis of a spatial biological gradient between Stations 1 and 2 to Station 7.

Macrobenthic communities at the Palos Verdes stations were characterized by an absence of the echinoderms and arenaceous foraminifera commonly found at Station 7 (Tables 2 and 3). Crustaceans were significantly less abundant (biomass and density) at Stations 1 through 4 within 5 km of the outfalls than at the other stations ($p < 0.05$). The density of molluscs was significantly less at Stations 1 through 3 and significantly greater at Station 5. Molluscan biomass was significantly greater at both Stations 4 and 5. Polychaetes were abundant at

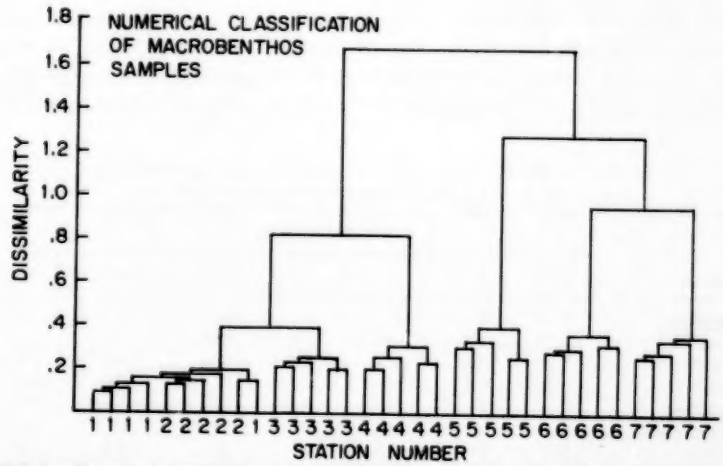

FIG. 2—*Numerical classification of macrobenthos samples. The station number is assigned to five replicates from each station.*

TABLE 2—*Mean density (N/0.1 m²) of benthic macrofauna at stations on the Palos Verdes Shelf and Santa Monica Bay, CA.*

Taxon	Station Number						
	1	2	3	4	5	6	7
Foraminifera	0	0	0	0	0.6	0.8	88.0
Mollusca	10.8	20.0	33.8	350.4	1608.2	344.6	74.6
Polychaeta	358.8	628.4	226.8	236.6	2177.0	533.2	205.2
Crustacea	1.4	10.8	15.6	7.0	86.0	147.0	100.0
Ophiuroidea	0	0	0	0	0	0.2	131.6
Other echinodermata	0	0	0.2	0	0	0	4.4
Other taxa	0.8	2.2	30.6	126.2	214.8	57.0	12.8
Totals	371.8	661.4	307.0	720.2	4086.6	1082.8	616.6

all stations ($N/0.1\ m^2 > 200$, $g/0.1\ m^2 > 2$), but significantly more abundant at Station 5. Biomass and individuals were most evenly distributed among taxa at Station 7.

There were major changes in species composition between stations (Table 4). The polychaete, *Capitella capitata*, was the dominant species at the three stations nearest (1 to 3 km) the outfalls. The clam, *Parvilucina tenuisculpta*, and the polychaetes, *Tharyx* sp. A and *Mediomastus californiensis* were dominant at Stations 4, 5, and 6, 5 to 15 km from the outfalls. The brittle star, *Amphiodia urtica* was the most abundant species at Station 7.

The structure of the entire macrobenthic assemblage reflected changes in species composition and abundance of the higher taxa (Table 5). The Infaunal Index decreased continuously from Station 7 to Stations 1 and 2. Biomass was significantly greater at Stations 4 and 5 than at all other stations. Differences in biomass between other stations were usually not significant, although the biomass at Station 1 was significantly less than at Station 7. Density at Station 5 was significantly greater than at all other stations. Results of the multiple range tests showed considerable overlap in significant ranges for differences in mean density

TABLE 3—*Mean biomass (g/0.1 m²) of the benthic macrofauna at stations on the Palos Verdes Shelf and Santa Monica Bay, CA.*

Taxon	Station Number						
	1	2	3	4	5	6	7
Foraminifera	0	0	0	0	<0.1	0.1	1.0
Mollusca	1.1	1.1	4.6	55.0	50.7	4.7	0.5
Polychaeta	5.2	10.6	1.8	4.4	12.6	7.0	2.2
Crustacea	<0.1	0.1	0.1	0.1	2.5	0.5	0.6
Ophiuroidea	0	0	0	0	0	<0.1	7.7
Other echinodermata	0	0	<0.1	0	0	0	2.9
Other taxa	0.1	0.1	3.3	2.0	2.7	8.6	0.5
Totals	6.4	11.9	9.8	61.5	68.5	20.9	15.4

TABLE 4—*Mean densities of the five most abundant species at at least one station on the Palos Verdes Shelf and Santa Monica Bay, CA. Five replicate 0.1 m² grabs were taken at each station.*

Species	Mean Number of Individuals/0.1 m²						
	Station Number						
	1	2	3	4	5	6	7
Eumida sanguinea (PO)	7.4	15.2	0.6	...	...	...	...
Schistomeringos longicornis (PO)	6.6	8.6	1.4	...	...	...	...
Nephtys cornuta franciscana (PO)	7.8	3.8	0.8	0.2	0.2	0.6	...
Capitella capitata (PO)	317.0	579.2	172.6	4.2	9.6	0.2	0.2
Macoma carlottensis (PE)	2.4	8.8	10.6	0.2	4.2	0.4	...
Nereis sp. A (PO)	10.6	6.0	11.4	5.2	26.8	6.4	0.2
Notomastus sp. A (PO)	...	...	0.2	17.8	27.6	2.6	...
Listriolobus pelodes (E)	...	...	28.6	6.0	45.2	24.4	0.8
Parvilucina tenuisculpta (PE)	3.6	2.6	12.2	335.4	1498.6	155.0	33.4
Tubulanus pellucidus (N)	...	...	0.6	15.2	56.8	12.2	0.6
Mediomastus californiensis (PO)	...	0.2	0.2	83.8	529.4	81.6	7.6
Tharyx sp. A (PO)	0.2	0.6	0.2	42.4	1194.0	113.8	0.8
Pectinaria californiensis (PO)	...	...	1.8	22.0	51.2	52.6	15.2
Euphilomedes sp. A (OS)	0.2	0.4	0.2	0.6	10.2	74.2	2.2
Spiophanes missionensis (PO)	...	...	1.8	2.8	67.6	74.2	39.2
Axinopsida serricata (PE)	...	...	...	0.4	15.8	95.4	21.0
Myriochele sp. M (PO)	...	...	...	...	...	0.8	53.0
Amphiodia urtica (OP)	...	...	...	...	...	0.2	131.0
Rhabdammina abyssorum (F)	...	...	...	...	...	...	71.6

NOTE—PO = polychaete, PE = pelecypod, E = echiuroid, N = nemertean, OS = ostracod, OP = ophiuroid, and F = foraminiferan.

TABLE 5—*Structure of the macrobenthic community at stations on the Palos Verdes Shelf and Santa Monica Bay, CA.*

	Station Number						
	1	2	3	4	5	6	7
Infaunal Index	4.6	2.8	18.4	37.1	51.8	63.0	80.8
Biomass (g/0.1 m^2)	6.4	11.9	9.8	61.5	68.5	20.9	15.4
Density (N/0.1 m^2)	371.8	661.4	307.0	720.2	4086.6	1082.8	616.6
Species richness (S/0.1 m^2)	15.8	18.6	28.2	41.2	96.6	72.4	73.4
Dominance (S/75% N)	1.0	0.9	4.6	2.8	2.6	10.8	11.5
Dominant species	*Capitella*	*Capitella*	*Capitella*	*Parvilucina*	*Parvilucina*	*Parvilucina*	*Amphiodia*
Amphipod density (N/0.1 m^2)	0	0	2.4	1.6	46.0	52.2	65.4
Phoxocephalid density (N/0.1 m^2)	0	0	0	0	30.6	40.8	31.4

at other stations. The mean species richness of 96.6 species/0.1 m^2 at Station 5 was significantly greater than at all other stations. Species richness was not different at Stations 6 and 7, but significantly more species were collected at both of these stations than at Stations 1 through 4. Significantly fewer species were collected at Stations 1 and 2 than at all other stations. The dominance index was significantly less at Stations 1 and 2 than at other stations, indicating the strong dominance of *Capitella capitata*. The dominance index was significantly greater at Stations 3, 6, and 7 than at the other stations. The density of all amphipods was significantly greater at Stations 5, 6, and 7 than at Stations 1 through 4. No amphipods were collected at Stations 1 and 2. There was no significant difference in the density of phoxocephalid amphipods at Stations 5, 6, and 7. No phoxocephalids were collected at Stations 1 through 4.

Chemistry

Numerical classification of the chemical data clustered samples in a pattern almost identical to that of the macrobenthic samples (Fig. 3). Samples from the same station always were placed in the same cluster indicating high within-station chemical similarity. Replicates from Stations 1 and 2 clustered together while all other clusters represented replicates from a single station. The hierarchial arrangement of the chemical sample clusters is consistent with a hypothesis of a spatial chemical gradient from Stations 1 and 2 to Station 7.

The spatial chemical gradient is very evident in the distribution of parameters related to both organic enrichment and contamination (Table 6). With few exceptions, mean values for total volatile solids, total organic carbon, ammonia-*N*, total and free sulfide, sediment BOD, total and hydrocarbon oil/grease, cadmium, lead, zinc, chromium, copper, and nickel were highest at Station 1 or 2,

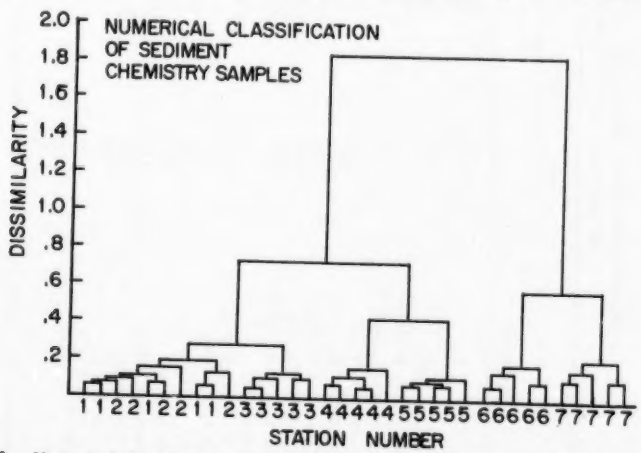

FIG. 3—*Numerical classification of sediment chemistry samples. The station number is assigned to five replicates from each station.*

TABLE 6—*Geochemical characteristics of Palos Verdes Shelf and Santa Monica Bay sediments. All bulk sediment concentrations are expressed on a dry weight basis. Data are mean values for five replicate grabs taken at each station.*

Parameter	Station Number						
	1	2	3	4	5	6	7
Eh, mV	−85	−49	−29	89	219	363	321
pH	7.2	7.2	7.2	7.7	7.8	7.7	8.1
Total solids, %	35.9	38.1	36.9	37.3	44.5	58.9	64.4
Total volatile solids, %	17.5	16.0	15.0	14.2	15.2	9.5	4.0
Total organic carbon, %	4.1	4.2	3.7	3.8	3.2	2.2	0.9
Ammonia-*N*, mg/L	2.4	2.8	1.4	0.40	0.34	0.56	0.44
Free sulfide, mg/L	11	23	6.7	0.49	0.65	0.41	0.33
Total sulfide, mg/kg	2520	1940	2370	1310	443	121	24
5-day BOD, mg/kg	13800	13900	10600	7160	4390	1740	656
Total oil/grease, mg/kg	20600	15300	9950	6180	3620	1020	338
Hydrocarbon oil/grease, mg/kg	10800	10100	7020	6490	3300	960	214
Cadmium, mg/kg	32	28	26	22	8.7	2.4	2.4
Lead, mg/kg	338	306	293	252	150	57	27
Zinc, mg/kg	853	781	584	709	339	130	95
Chromium, mg/kg	821	706	481	721	305	101	62
Copper, mg/kg	691	634	450	547	309	96	52
Nickel, mg/kg	95	89	99	85	61	26	61
Sand, %	23.8	23.5	12.7	10.2	23.6	18.2	38.0
Silt, %	60.3	60.7	68.7	68.8	56.5	74.1	53.7
Clay, %	15.9	15.8	18.6	21.0	19.9	7.7	8.3

intermediate at Stations 3 through 6, and lowest at Station 7. Results of the multiple-range tests showed significant differences between means along the spatial gradient, although there was often overlap in significant ranges between adjacent stations. Total solids, Eh, and pH values generally increased with distance from the outfalls. Particle size fractions (percent sand, percent silt, and percent clay) did not follow any regular spatial trend. Percent sand, for example, decreased from ~23% at Stations 1 and 2 to 10.1% at Station 4 and then increased to 38.0% at Station 7. Qualitative examination of the sand fraction at stations near the outfalls indicated that it was composed principally of organic particles. Sand at the reference station was composed principally of mineral matter.

The most concentrated organic priority pollutants found in the sediment samples were bis(2-ethylhexyl) phthalate and 2,2-bis (4-chlorophenyl) 1,1-dichloroethene (4,4′-DDE) (Table 7). The highest concentration of DDE was found at Station 4, 5 km from the outfalls. Certain aspects of the organic priority pollutant data are inexplicable, such as the rarity of base/neutral compounds at Station 1 and the high concentration of di-*n*-butyl phthalate at Station 7. Only three compounds were detected at all stations: bis(2-ethylhexyl) phthalate, 4,4′-DDE, and phenol.

Sediment Toxicity

Mean survival of *R. abronius* in sediment from the Palos Verdes Shelf and Santa Monica Bay stations ranged from 15.4 to 19.4 amphipods for bioassays with 20 individuals in each of five replicates for each station (Table 8). Mean survival for Stations 1, 2, and 3, was significantly less than the Yaquina Bay control mean (19.6). Lowest survival in a single replicate (12 amphipods) occurred at Station 1.

Correlation Between Geochemistry, Biology, and Toxicity

Results of Kendall's rank correlations showed that seven parameters were significantly correlated with relatively few of the 31 parameters included in this analysis (Table 9). Percent clay was not significantly correlated with any other parameter. Percent silt and percent sand were correlated only with each other. Benthic biomass and density were correlated with each other and with species richness, but with only one geochemical parameter (ammonia-*N* or nickel). Ammonia-*N* and 4,4′-DDE were correlated with five and seven parameters, respectively.

The remaining 24 parameters included in the correlation analysis were usually significantly correlated with one another (Table 10). Total and hydrocarbon oil/grease and lead were significantly correlated with every parameter tested except the seven listed in Table 9. Twenty-one parameters, including bioassay survival, were significantly correlated with at least 18 parameters. Phenol, dominance, and nickel were correlated with between 11 and 16 parameters.

TABLE 7—*Concentration of priority pollutant organic compounds in Palos Verdes Shelf and Santa Monica Bay sediments (μg/kg dry weight). Data are mean values for two replicate grabs taken at each station.*

Compounds	Station Number						
	1	2	3	4	5	6	7
ACID COMPOUNDS							
Phenol	1040	112	145	122	70	<9	18
2,4 dimethylphenol	40	...	...	...	...	...	...
Pentachlorophenol	...	...	342	...	...	...	...
BASE/NEUTRAL COMPOUNDS							
Acenaphthylene	...	160	54	81	44	14	...
Naphthalene	...	29	...	20	13	930	...
Anthracene	...	623	...	197	...	35	...
Fluoranthene	...	294	92	98	...	...	...
Phenanthrene	...	290	...	...	...	...	...
Benzo[a]anthracene	...	1330	...	...	...	...	...
Benzo[b]fluoranthene	...	633	...	338	...	...	...
Pyrene	...	838	184	198	118	...	...
Chrysene	...	606	...	...	...	...	...
Diethyl phthalate	...	...	1450	...	...	20	278
Di-*n*-butyl phthalate	...	215	217	183	118	18	355
Di-*n*-octyl phthalate	...	388	92	...	...	...	42
Bis(2-ethylhexyl) phthalate	12730	25380	8800	7200	5121	1010	138
Butyl benzyl phthalate	415	613	197	...	...	...	...
PESTICIDES							
4,4′-DDT	102	...	64	74	...	...	...
4,4′-DDE	5610	3940	5920	7833	1460	972	56
4,4′-DDD	1530	442	1300	770	72	130	...
Dieldrin	...	12	...	...	...	...	...

TABLE 8—*Mean and standard error (in parentheses) of* Rhepoxynius abronius *survival in sediment from the Palos Verdes Shelf and Santa Monica Bay, CA. Twenty amphipods were added to five replicate sediment samples from each station. Underlined means are not significantly different from survival in Yaquina Bay control sediment* ($p < 0.05$).

Station Number							
1	2	3	4	5	6	7	Yaquina Bay Control
15.4(1.08)	16.0(1.19)	16.0(1.05)	18.4(0.40)	16.8(0.97)	19.4(0.25)	19.0(0.32)	19.6(0.25)

TABLE 9—*Biological and geochemical parameters that were significantly correlated ($\alpha = 0.05$) with few other parameters.*[a]

Parameter	Number of Nonsignificant Correlations	Significant Correlations	
		Number	Parameters
4,4′-DDE	23	7	percent solids, total sulfides, Zn, Cr, Cu, phenol, phoxocephalid density
Ammonia-*N*	25	5	pH, BOD, Infaunal Index, biomass, species richness
Benthic biomass	27	3	ammonia-*N*, benthic density, species richness
Benthic density	27	3	nickel, biomass, species richness
Sand, %	29	1	Silt, %
Silt, %	29	1	Sand, %
Clay, %	30	0	

[a]31 parameters: phenol, 4,4′-DDE, bis(2-ethylhexyl) phthalate, bioassay survival plus those listed in Tables 5 and 6.

Comparison of Geochemical and Biological Conditions in Toxic and "Nontoxic" Sediment

Geochemical and biological data collected at Stations 1, 2, and 3 were pooled to represent conditions where sediment was acutely toxic to *Rhepoxynius abronius*. These data were then compared with conditions at Stations 4, 5, and 6 where sediment was not acutely toxic to *R. abronius* (Table 11). Data from Station 7 were excluded from this comparison because it is not influenced by the Los Angeles County discharge. The toxic sediment stations had significantly fewer species, individuals, and biomass. They were strongly dominated by *Capitella capitata*. The abundance of all amphipod species was significantly reduced at the toxic sediment stations, and phoxocephalid amphipods were completely absent. Indicators of organic enrichment (Eh, total volatile solids, BOD) and chemical contamination (oil/grease, cadmium, chromium, bis(2-ethylhexyl) phthalate) were significantly greater at the toxic sediment stations. The concentration of DDE was not significantly different between the two station groups.

Discussion

The distribution of the macrobenthos on the Palos Verdes Shelf was generally consistent with the Pearson-Rosenberg [*15*] model of benthic succession in relation to organic enrichment. Species richness, density, and biomass increased greatly in areas of moderate organic enrichment at Station 5, 9 km from the Los Angeles County sewage outfalls and decreased to or below reference conditions within 3 km of the discharge (Fig. 4). The Pearson-Rosenberg model predicts a "peak of opportunists" due to increased population densities of a few species at relatively high levels of organic enrichment. The opportunistic polychaete, *Capitella capitata*, reached densities >500 individuals/0.1 m^2 about 1 km from the outfalls. Use of a 1.0-mm screen may have underestimated the density of this

TABLE 10—*Twenty-four biological and geochemical parameters that were significantly correlated ($\alpha = 0.05$) with many other parameters.*[a]

Parameter	Number of Significant Correlations	Nonsignificant Correlations	
		Number	Parameters
Total oil/grease	23	0	...
Hydrocarbon oil/grease	23	0	...
Lead (Pb)	23	0	...
BOD	22	1	Ni
Zinc (Zn)	22	1	Ni
Copper (Cu)	22	1	Ni
bis(2-ethylhexyl) phthalate	22	1	Ni
Infaunal Index	22	1	Ni
Eh	22	1	Dominance
Cadmium (Cd)	22	1	Dominance
Solids, %	22	1	Dominance
Total sulfides	22	1	Dominance
Free sulfides	21	2	Ni, phenol
Amphipod density	21	2	Ni, phenol
Phoxocephalid density	20	3	Dominance, species richness, total volatile solids
Chromium (Cr)	20	3	Ni, pH, bioassay survival
Total organic carbon	20	3	Ni, phenol, bioassay survival
Total volatile solids	19	4	Ni, phenol, pH, phoxocephalid density
Bioassay survival	18	5	Dominance, pH, Cr, species richness, total organic C
Species richness	18	5	Ni, dominance, phenol, bioassay survival, phoxocephalid density
pH	18	5	Dominance, phenol, Cr, bioassay survival, total volatile solids
Phenol	16	7	Dominance, pH, free sulfide, amphipod density, species richness, total organic C, total volatile solids
Dominance	13	10	Ni, Eh, Cd, phenol, pH, species richness, solids (%), total sulfide, phoxocephalid density, bioassay survival
Nickel (Ni)	11	12	Dominance, Zn, Cr, Cu, Infaunal Index, bis(2-ethylhexyl) phthalate, total volatile solids, total organic C, free sulfide, BOD, species richness, amphipod density

[a]Excludes seven compounds listed in Table 9.

small worm. The "peak" of *Capitella capitata* was quantitatively overshadowed by densities >1000 individuals/0.1 m^2 for both the clam, *Parvilucina tenuisculpta*, and the polychaete, *Tharyx* sp. A at Station 5.

The high density of the macrobenthos at Station 5 was not due to just a few very successful species. Significantly more species were collected there than at any other site including the reference station. Station 5 lies in the middle of a

TABLE 11—*Comparison of geochemical and biological conditions in toxic and "nontoxic" sediment. Toxic sediment was collected from stations on the Palos Verdes Shelf, CA, where survival in sediment bioassays was significantly less than in control sediment. "Nontoxic" sediment was collected at stations where survival was not significantly different from control survival.*

	Toxic Sediment	"Nontoxic" Sediment	Statistical Comparison, *t*
Station Numbers	1, 2, 3	4, 5, 6	...
Survival	15.8	18.1	3.25[a]
Infaunal Index	8.6	50.6	10.90[a]
Biomass (g/0.1 m^2)	9.4	50.3	6.26[a]
Density (N/0.1 m^2)	446.7	1963.2	3.53[a]
Species richness (S/0.1 m^2)	20.9	70.1	7.58[a]
Dominance (S/75% N)	2.2	5.4	2.67[b]
Dominant species	*Capitella*	*Parvilucina*	
Amphipod density (N/0.1 m^2)	0.8	33.3	4.94[a]
Phoxocephalid density (N/0.1 m^2)	0.0	23.8	[c]
Eh	−54.3	223.7	5.59[a]
Total volatile solids, %	16.2	13.0	4.20[a]
BOD (g/kg)	12.8	4.4	10.00[a]
Total oil/grease (g/kg)	15.3	3.6	8.68[a]
Cadmium (mg/kg)	28.7	11.1	6.94[a]
Chromium (mg/kg)	669.3	375.8	3.21[a]
Bis(2-ethylhexyl) phthalate (mg/kg)	15.6	4.4	2.64[b]
4,4'-DDE (mg/kg)	5.2	3.4	0.89 NS[d]

[a] $p < 0.01$.
[b] $p < 0.05$.
[c] Statistical comparison not possible.
[d] NS = not significant.

strong biological gradient that is evident in the classification analysis of macrobenthos samples (Fig. 2) and in the overlap in the distribution of individual species (Table 4). Although some species (for example, *Euphilomedes* sp. A) were present at all stations, their relative abundance indicates greater success at particular portions of the gradient. The distribution of other species was discontinuous and favored conditions near the outfalls (for example, *Eumida*

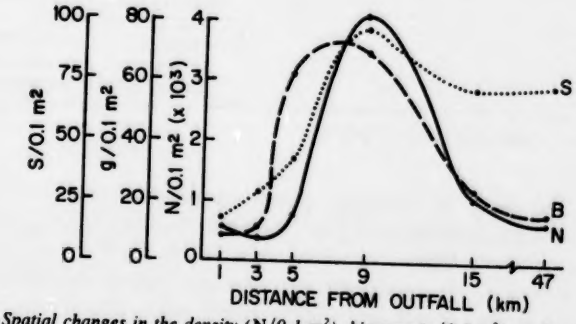

FIG. 4—*Spatial changes in the density (N/0.1 m^2), biomass (g/0.1 m^2), and species richness (S/0.1 m^2) of the macrobenthos near the Los Angeles County sewage outfalls.*

sanguinea), at intermediate stations (for example, *Notomastus* sp. A), and at the reference station (for example *Amphiodia urtica*). The high species richness at Station 5 was not caused by an overlap between two well-defined communities at the ends of the biological gradient. Several of the dominants at both the reference station and near the outfalls were not collected at Station 5 (Table 4). The increased species richness, density, and biomass at this station reflect a general stimulation of a unique macrobenthic assemblage on the 60-m contour. This assemblage varied continuously along the spatial gradient due to the integration of individual species distributions [*15*].

The Pearson-Rosenberg model provides a conceptual framework for defining the assimilative capacity of benthic ecosystems for organic wastes. Ecological conditions at Station 5 are probably close to the optimal limits of that assimilation. The structure of the benthic assemblages at Stations 1 to 4 indicates that additional organic loading at Station 5 would reduce species richness and abundance of the macrobenthos. Chemical characteristics of sediment at Station 5, therefore, may be pertinent to the regulation of sewage discharges. All parameters of organic enrichment show that Station 5 lies in the midst of an enrichment gradient (Table 6). Percent volatile solids and total organic carbon at this station were generally less than values closer to the outfalls, but the differences are relatively small. The much greater differences in Eh, BOD, free and total sulfides indicate that the upper 2 cm of sediment at Station 5 were aerobic while sediment closer to the outfalls was increasingly anaerobic. Thus, the unique qualitative features of sediment at Station 5 appear to be aerobic conditions in the presence of abnormally high concentrations of organic matter.

Spatial gradients of organic enrichment, chemical contamination, sediment toxicity, and macrobenthic conditions are superimposed on one another on the Palos Verdes Shelf. Most biological and geochemical parameters were therefore significantly correlated [*2,12,13*] (Table 10). Exceptions to this general spatial correlation of benthic parameters include percent sand, percent silt, percent clay, benthic density, biomass, ammonia-*N*, and 4,4′-DDE (Table 9). The distribution of percent sand was unique because it was relatively high near the outfalls due to organic particles and also high at Station 7 due to a mineral fraction. The Los Angeles County Sanitation Districts (LACSD) [*12*] also reported large quantities of sand-size vegetative particles of sewage origin near the outfalls. Percent silt was inversely related and significantly correlated only with percent sand. Clay accounted for no more than 21% of the sediment and was not significantly correlated with any parameter. Benthic biomass and density were significantly correlated with each other and with species richness. Each of these biological parameters reached maximum values at Station 5. While most parameters varied continuously between extreme values at both ends of the gradient, ammonia-*N* decreased to a background level of ~0.4 mg/L at Station 4. The DDE concentration was greatest at Station 4, 5 km from the outfalls. The discharge of DDT through the Los Angeles County sewage outfalls was greatly reduced by source control from an annual discharge of 100 metric tons (MT) in 1970 to 4 MT in

1973 to 0.5 MT in 1980 [*12*]. The distribution of DDE in 1980 may reflect burial of highly contaminated sediments near the outfalls or the gradual transport of this contaminant along the Palos Verdes Shelf.

Three geochemical parameters (total and hydrocarbon oil/grease, lead) were significantly correlated with all parameters except the seven just discussed. Swartz et al [*9*] found that total oil/grease and hydrocarbon oil/grease were the only parameters consistently correlated with toxicity in bioassays of sewage sludges from six treatment plants including the Los Angeles County plant. The present results support their suggestion that oil/grease may provide an integrative measure of the overall level of contamination.

The Infaunal Index was significantly correlated with more sediment parameters than any other biological index. However, it was not significantly correlated with either the density or biomass of the macrobenthos. Reduction of index values reflects a change from the assemblage that would naturally occur at 60 m in the Southern California Bight, but does not necessarily indicate a degradation of the benthos. This index was originally developed as a trophic index to describe the feeding behavior of soft-bottom benthic communities [*20*]. It has been applied in marine pollution assessments to indicate the condition of benthic assemblages [*2,13*] and to predict biological responses to organic enrichment [*28*]. This application is not dependent on the "trophic" orientation of the index. The index formula can be applied to a classification of species based on empirical descriptions of their distributions around sewage outfalls. Selection of species to be included in the index computation is obviously site specific. Word's [*20*] list of 53 taxa is applicable to depths as great as 800 m in the Southern California Bight.

Data from the present survey show that Infaunal Index values at 60 m on the Palos Verdes Shelf in May 1980 were determined principally by only 5 of the 53 taxa: *Capitella capitata, Tharyx* sp. A, *Mediomastus californiensis, Parvilucina tenuisculpta,* and *Amphiodia urtica* (Table 12). Reduction of the species list to a few well-known indicator species would simplify at least the calculation of index values. The Infaunal Index (or any other index) should not be used as

TABLE 12—*Influence of dominant species on the Infaunal Index.*

Station Number	Normal Index (53 taxa)	Index Based on Five Dominant Species[a]	Index Excluding Five Dominant Species[a] (48 taxa)
1	4.6	0.5	36.1
2	2.8	0.3	35.6
3	18.4	7.9	41.8
4	37.1	41.9	24.1
5	51.8	50.4	61.7
6	63.0	51.6	71.1
7	80.8	86.7	78.0

[a]*Capitella capitata, Tharyx* sp. A, *Mediomastus californiensis, Parvilucina tenuisculpta, and Amphiodia urtica.*

the sole criterion of biological conditions. It is still necessary to sort, count, and identify all species in a benthic sample in order to estimate classic biological parameters like species richness, biomass, and density.

"Field validation" of bioassays is a relatively new and important research topic in pollution ecology. The objective is to determine the ecological relevance of bioassay results obtained under laboratory conditions. The strong pollution gradient on the Palos Verdes Shelf provided an opportunity to compare data from the sediment bioassay with the spatial distribution of the macrobenthos and sediment contamination. The sediment bioassay results were quite relevant to pollution on the Shelf. Statistically significant rank correlations occurred between sediment toxicity and 18 biological and geochemical parameters including phoxocephalid density, total amphipod density, and various measures of organic enrichment and chemical contamination (Table 10). Mean survival in sediment from the three stations within 3 km of the outfalls was significantly less than in control sediment (Table 8). This result is consistent with LACSD's [*12*] observation that the zone of maximum deposition extends 3 km to the northwest along the 60-m contour. Significant reductions in macrobenthic species richness, density, biomass, and Infaunal Index occurred at the three stations with sediment acutely toxic to *R. abronius* (Table 11). No phoxocephalids were collected at these stations, and the density of all amphipods was reduced to $<1/0.1$ m^2.

The degree of sediment toxicity on the Palos Verdes Shelf was not as great as that determined by phoxocephalid bioassays in other contaminated benthic habitats [*8,29*]. The lowest mean survival (15.4) and lowest survival in a single replicate (12) occurred at Station 1 (Table 8). In contrast, Swartz et al [*8*] found that a mean of only 10.8 amphipods survived for ten days in 129 sediment samples from the waterways of Commencement Bay, WA. No amphipods survived in 16 of the Commencement Bay samples. The relatively low acute toxicity of Palos Verdes Shelf sediments may reflect a reduced bioavailability of chemical contaminants that are bound to high concentrations of organic matter.

There were some exceptions to the generally close relationship between sediment toxicity and environmental gradients on the Shelf. Bioassay survival was not significantly correlated with seven parameters that were poorly related to most factors (Table 9). Within this group, the lack of correlation between sediment concentrations of DDE and survival of a sensitive infaunal amphipod is of particular interest. DDT has previously been linked to the rarity of crustaceans on the Shelf [*12,13*], although there is no direct evidence for this relationship. Survival was also not correlated with total organic carbon and chromium, but concentrations of both these parameters were significantly higher at the three stations with acutely toxic sediment. Phoxocephalid amphipods were not collected at four stations (1 to 4), but significant reductions in survival only occurred at three stations (1 to 3). This discrepancy may reflect the inherent limitation of a short-term laboratory test to indicate precisely effects of chronic exposure in the field. The spatial distribution of phoxocephalid amphipods provides a more

reliable indication of chronic impacts, and our results show that phoxocephalid density was significantly correlated with DDE sediment concentrations (Table 9).

The amphipod bioassay has potential application in pollution monitoring to detect sites of sediment contamination [*5*]. The method is inexpensive and rapid, but not particularly sensitive to environmental degradation. The present study and an earlier "field validation" in Commencement Bay, WA [*8*] have shown that sediment toxic to *R. abronius* is usually associated with major perturbations of benthic communities. The bioassay can be used most effectively in monitoring to identify sites of greatest concern where more sensitive and resource-intensive methods should be applied. The sediment toxicity survey should not be an end in itself. In particular, the absence of statistically significant evidence for sediment toxicity does not demonstrate absence of deleterious environmental impacts.

Bascom et al [*2,13*] classified macrobenthic conditions near sewage outfalls in the Southern California Bight as "normal," "changed," or "degraded" on the basis of Infaunal Index, biomass, species richness, density, sediment BOD, and total volatile solids. With a few exceptions, the present results are consistent with their classification. Stations 6 and 7 are classified as "normal" because of Infaunal Index values >60. About 72 species/0.1 m^2 were collected at these stations, while "normal" species richness at this depth is about 74 species/0.1 m^2. Stations 1, 2, and 3 are classified as "degraded" because of Infaunal Index values <30. The present data show that species richness is greatly reduced at these stations, but density is about the same as "normal." Biomass at all three stations was less than at the reference station, while the classification shows biomass under "degraded" conditions to be many times greater than "normal." Stations 4 and 5 are classified as "changed" because of Infaunal Index values between 30 and 60. There was a much greater enhancement of biological conditions at Station 5 than would be expected by the classification. Species richness increased rather than decreased relative to "normal" conditions. Both biomass and density were several times greater than expected. Organic enrichment was also much greater than expected for a mean Infaunal Index of 51.8. We agree with Bascom et al [*13*] that structural alterations associated with a "changed" macrobenthos do not indicate biological damage. The benthos at Station 5 is a good example of what Anger [*30*] described as transforming sewage particulates into available fish food. However, Anger also emphasized that this process creates the danger of introducing toxic chemicals into the food web. Unless this potential damage is mitigated through source control or effluent treatment, the potential benefit of this additional fish food could be deceptive. The biological tissue concentration of metals on the Palos Verdes Shelf generally does not change throughout the food web, but organic mercury and synthetic organic compounds increase with trophic level [*2*].

Both organic enrichment and chemical contamination may affect the macrobenthos of the Palos Verdes Shelf. The general agreement of benthic distributions

on the Shelf with predictions of the Pearson-Rosenberg [*15*] model and the quantitative benthic classification of Bascom et al [*2,13*] suggest that enrichment has the predominant effect. Enhancement of the macrobenthos in areas of moderate organic enrichment is clearly caused by the addition of energy from the benthic deposition of sewage particulates. Cause of the degradation of the macrobenthos closer to the outfalls is less certain. Two factors may contribute to the decline: creation of anaerobic conditions by overenrichment and toxic action of chemical contaminants [*10,12,13*]. The success of species known to be tolerant to low-oxygen concentrations (*Capitella capitata* [*31*]), indicates the absence of less tolerant species may be due to anaerobic conditions. Chemical contamination is implicated by the acute toxicity of sediment to *Rhepoxynius abronius* under aerobic laboratory conditions and the correlation of sediment toxicity with the distribution of amphipods. Chemical contamination and anaerobic conditions are not mutually exclusive. Both may contribute to environmental stress on the Palos Verdes Shelf.

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